A REMARK ON NEUTRINO OSCILLATIONS OBSERVED IN KamLAND EXPERIMENT

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Abstract

It is demonstrated that the observation of neutrino oscillations in the atmospheric (K2K) neutrino experiments and unitarity of the mixing matrix implies that disappearance of the reactor $\bar{\nu}_e$'s discovered in the KamLAND experiment is due to $\bar{\nu}_e \to \bar{\nu}_\mu$ *and* $\bar{\nu}_e \to \bar{\nu}_\tau$ transitions. At $\theta_{23} = \pi/4$ the probabilities of these transitions are equal.

At the Neutrino 2004 conference a new important result of the KamLAND collaboration was reported: the significant distortion of the spectrum of the reactor $\bar{\nu}_e$ was observed [1].

As it is well known, in the KamLAND experiment the $\bar{\nu}_e$'s from many reactors in Japan and Korea are detected via the observation of e^+ and n produced in the reaction

$$\bar{\nu}_e + p \to e^+ + n \tag{1}$$

In the paper [1] it is written " We present an improved measurement of the oscillations between first two neutrino families....."

In the framework of the standard three neutrino mixing

$$\nu_{lL} = \sum_{i=1}^{3} U_{li} \nu_{il} \tag{2}$$

($U^\dagger U = 1$, ν_i is the field of neutrino with mass m_i) we will consider here neutrino oscillations in the KamLAND experiment.

The transition probabilities of neutrino and antineutrinos can be presented in the form (see [2])

$$\mathrm{P}(\nu_l \to \nu_{l'}) = |\delta_{ll'} + \sum_{i=2,3} U_{l'i} U_{li}^* \; (e^{-i\Delta m_{1i}^2 \frac{L}{2E}} - 1)|^2 \tag{3}$$

and

$$\mathrm{P}(\bar{\nu}_l \to \bar{\nu}_{l'}) = |\delta_{ll'} + \sum_{i=2,3} U^*_{l'i} U_{li} \ \ (e^{-i\Delta m^2_{1i}\frac{L}{2E}} - 1)|^2 \tag{4}$$

Here L is the source-detector distance, E is the neutrino energy and $\Delta m^2_{1i} = m^2_i - m^2_1$.

From the analysis of the existing neutrino oscillation data two important features of the neutrino mixing emerged:

1. $\Delta m^2_{12} \ll |\Delta m^2_{13}|$
2. $|U_{e3}|^2 = \sin^2 2\theta_{13} \ll 1$

It follows from 1. and 2. that the dominant transition in the atmospheric range of L/E is $\nu_\mu \to \nu_\tau$ ($\bar{\nu}_\mu \to \bar{\nu}_\tau$). For the ν_μ ($\bar{\nu}_\mu$) survival probability from (3) and (4) we find

$$\mathrm{P}(\nu_\mu \to \nu_\mu) = \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_\mu) \simeq 1 - 2|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) \ \ (1 - cos\Delta m^2_{13}\frac{L}{2E}). \tag{5}$$

In the approximation $\sin^2 2\theta_{13} \to 0$ we have

$$U_{\mu 3} = \sin\theta_{23}, \quad U_{\tau 3} = \cos\theta_{23}. \tag{6}$$

Thus, in the atmospheric range of L/E we obtain

$$\mathrm{P}(\nu_\mu \to \nu_\mu) = \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_\mu) \simeq 1 - \frac{1}{2} \ \ \sin^2 2\,\theta_{23} \ \ (1 - cos\Delta m^2_{13}\frac{L}{2E}). \tag{7}$$

From the analysis of the Super-Kamiokande atmospheric neutrino data the following best-fit values of the parameters were found [3]

$$\sin^2 2\,\theta_{23} = 1; \quad \Delta m^2_{13} = 2 \cdot 10^{-3}\,\mathrm{eV}^2 \tag{8}$$

For the probability of the transition $\bar{\nu}_e \to \bar{\nu}_l$ in the KamLAND range of L/E from (4) (in the approximation $\sin^2 2\theta_{13} \to 0$) we find

$$\mathrm{P}(\bar{\nu}_e \to \bar{\nu}_l) = |\delta_{el} + U^*_{l2} U_{e2} \ \ (e^{-i\Delta m^2_{12}\frac{L}{2E}} - 1)|^2 \tag{9}$$

From this expression we obtain

$$\mathrm{P}(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - 2|U_{e2}|^2(1 - |U_{e2}|^2) \ \ (1 - cos\Delta m^2_{12}\frac{L}{2E}). \tag{10}$$

Further from the unitarity of the mixing matrix we have

$$U_{e1} \simeq \cos\theta_{12}, \quad U_{e2} \simeq \sin\theta_{12}. \tag{11}$$

Thus, in the the KamLAND range of L/E the $\bar{\nu}_e$ survival probability is given by the expression

$$\mathrm{P}(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \frac{1}{2}\ \sin^2 2\theta_{12}\ (1 - cos\Delta m^2_{12}\frac{L}{2E}). \tag{12}$$

From the analysis of the latest KamLAND data and solar neutrino data in [1] it was found

$$\Delta m^2_{12} = (8.2^{+0.6}_{-0.5}) \cdot 10^{-5}\,\mathrm{eV}^2;\ \tan^2 2\theta_{12} = 0.40^{+0.09}_{-0.07}. \tag{13}$$

The unitarity of the neutrino mixing matrix implies

$$\mathrm{P}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - (\mathrm{P}(\bar{\nu}_e \to \bar{\nu}_\mu) + \mathrm{P}(\bar{\nu}_e \to \bar{\nu}_\tau)) \tag{14}$$

From (9) for the probabilities of the transitions $\bar{\nu}_e \to \bar{\nu}_\mu$ and $\bar{\nu}_e \to \bar{\nu}_\tau$ we find the following expressions

$$\mathrm{P}(\bar{\nu}_e \to \bar{\nu}_\mu) \simeq 2|U_{e2}|^2|U_{\mu 2}|^2\ (1 - \cos\Delta m^2_{12}\frac{L}{2E}). \tag{15}$$

and

$$\mathrm{P}(\bar{\nu}_e \to \bar{\nu}_\tau) \simeq 2|U_{e2}|^2|U_{\tau 2}|^2\ (1 - \cos\Delta m^2_{12}\frac{L}{2E}). \tag{16}$$

The elements $U_{\mu 2}$ and $U_{\tau 2}$ are determined by the angles θ_{12} and θ_{23}. In fact, from the unitarity of the mixing matrix we have

$$\sum_{i=1,2} |U_{\mu i}|^2| = \cos^2\theta_{23};\quad \sum_{i=1,2} |U_{\tau i}|^2| = \sin^2\theta_{23} \tag{17}$$

Taking into account that the raws of the mixing matrix must be orthogonal we easily find

$$U_{\mu 2} = \cos\theta_{23}\ \cos\theta_{12};\quad U_{\tau 2} = -\sin\theta_{23}\ \cos\theta_{12}. \tag{18}$$

Thus, we have

$$\mathrm{P}(\bar{\nu}_e \to \bar{\nu}_\mu) = \cos^2\theta_{23}\,\frac{1}{2}\,\sin^2\theta_{12}\ (1 - cos\Delta m^2_{12}\frac{L}{2E}). \tag{19}$$

and

$$P(\bar{\nu}_e \to \bar{\nu}_\tau) = \sin^2\theta_{23}\,\frac{1}{2}\,\sin^2\theta_{12}\;(1 - cos\Delta m^2_{12}\frac{L}{2E}). \tag{20}$$

From (14), (19) and (20) we find the following relations between transition probabilities in the KamLAND range of L/E:

$$P(\bar{\nu}_e \to \bar{\nu}_\mu) = \cos^2\theta_{23}\,(1 - P(\bar{\nu}_e \to \bar{\nu}_e)) \tag{21}$$

and

$$P(\bar{\nu}_e \to \bar{\nu}_\tau) = \sin^2\theta_{23}\,(1 - P(\bar{\nu}_e \to \bar{\nu}_e)) \tag{22}$$

From these relations it follows that

$$P(\bar{\nu}_e \to \bar{\nu}_\tau) = \tan^2\theta_{23}\,P(\bar{\nu}_e \to \bar{\nu}_\mu). \tag{23}$$

Therefore the observation of neutrino oscillations in the atmospheric (K2K) experiments and the unitarity of the neutrino mixing matrix imply that the disappearance of reactor ν_e, observed in the KamLAND experiment, is due to $\bar{\nu}_e \to \bar{\nu}_\mu$ and $\bar{\nu}_e \to \bar{\nu}_\tau$ transitions. For $\theta_{23} = \pi/2$ (the SK best-fit value) the probabilities $P(\bar{\nu}_e \to \bar{\nu}_\mu)$ and $P(\bar{\nu}_e \to \bar{\nu}_\tau)$ are equal. [1]

Thus, in the leading approximation neutrino oscillations observed in the atmospheric (K2K) experiments are driven by Δm^2_{13} and are oscillations between second and third neutrino families. Neutrino oscillations observed in the KamLAND (solar) neutrino experiments are driven by Δm^2_{12}. Due to the unitarity of the mixing matrix all three neutrino families are involved in the oscillations.

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References

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[1] For arguments in favor of this equality see [4]

[4] E.K. Akhmedov, Nucl. Phys. Proc. Suppl. 118 (2003) 245; hep-ph/0207342.